Parallelized Multilevel Characteristic Basis Function Method Applied to Scattering Model For Forest Remote Sensing

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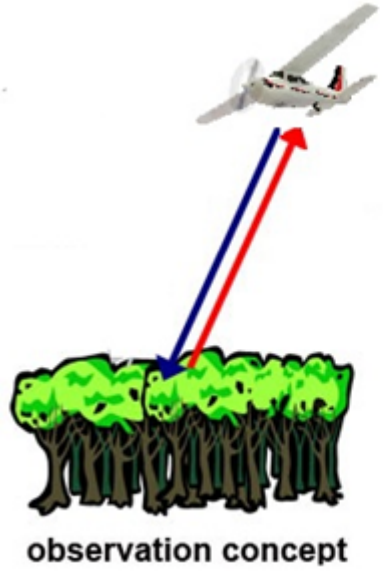
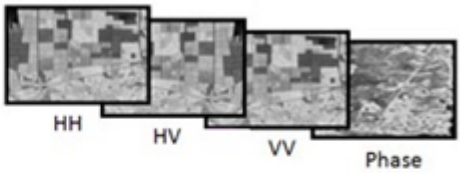
Introduction

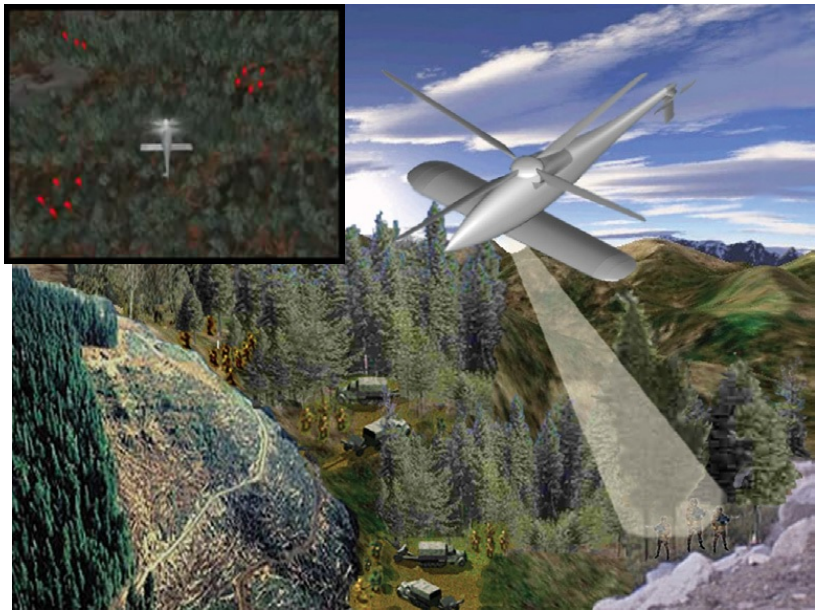
Analysis of forest cover





Geophysical products

- Forest biomass
- Forest height
- Forest biomass temporal change
- Forest disturbance



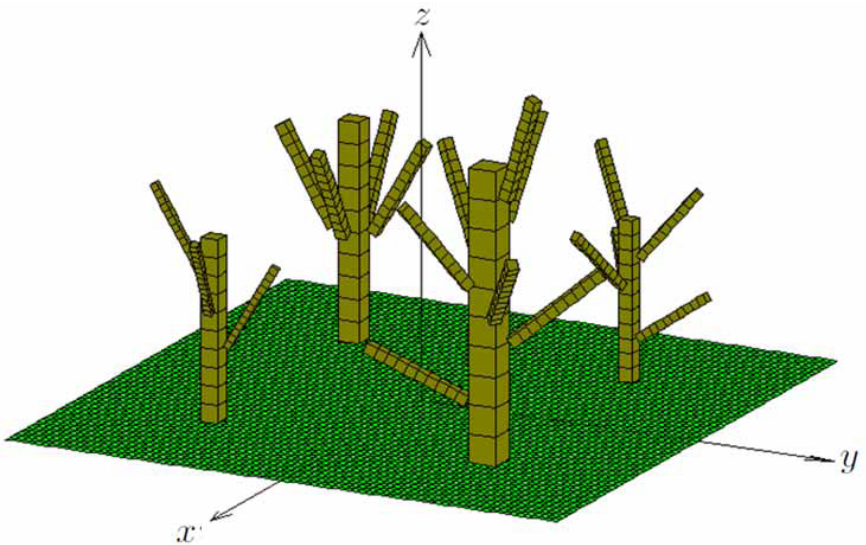
* BIOMASS, Thuy Le Toan, *Journées TOSCA-TropiSAR, Toulouse 19-20 Janvier 2011*

* Project FORESTER, Department of Defense or the U.S. Government and DARPA

A coherent forest scattering model to characterize the interactions between the main forest components and an electromagnetic plane wave

Introduction

3D full-wave model, based on the integral representation of the electric field (EFIE)



* S. Bellez , PhD thesis, UPMC 2010

Discretization of the EM problem into N cells

$$\underbrace{\begin{bmatrix} [\mathrm{Z}_{xx}^{mn}] & [\mathrm{Z}_{xy}^{mn}] & [\mathrm{Z}_{xz}^{mn}] \\ [\mathrm{Z}_{yx}^{mn}] & [\mathrm{Z}_{yy}^{mn}] & [\mathrm{Z}_{yz}^{mn}] \\ [\mathrm{Z}_{zx}^{mn}] & [\mathrm{Z}_{zy}^{mn}] & [\mathrm{Z}_{zz}^{mn}] \end{bmatrix}}_{\underline{\mathbf{Z}}} \underbrace{\begin{bmatrix} [\mathrm{E}_x^n] \\ [\mathrm{E}_y^n] \\ [\mathrm{E}_z^n] \end{bmatrix}}_{\underline{\mathbf{E}}} = \underbrace{\begin{bmatrix} [\mathrm{E}_x^{\mathrm{ref},m}] \\ [\mathrm{E}_y^{\mathrm{ref},m}] \\ [\mathrm{E}_z^{\mathrm{ref},m}] \end{bmatrix}}_{\underline{\mathbf{E}}^{\mathrm{ref}}}$$

Method of Moments (MoM)

- **Problem:** Rigorous numerical methods can become untenable when the problem become so large as to be computationally expensive both in terms of CPU time and memory.
- **Solution:** Use of basis functions adapted to the problem of interest.

Characteristic Basis Function Method (CBFM)

Plan

1. Characteristic Basis Function Method (CBFM)

1.1. Motivations et advantages

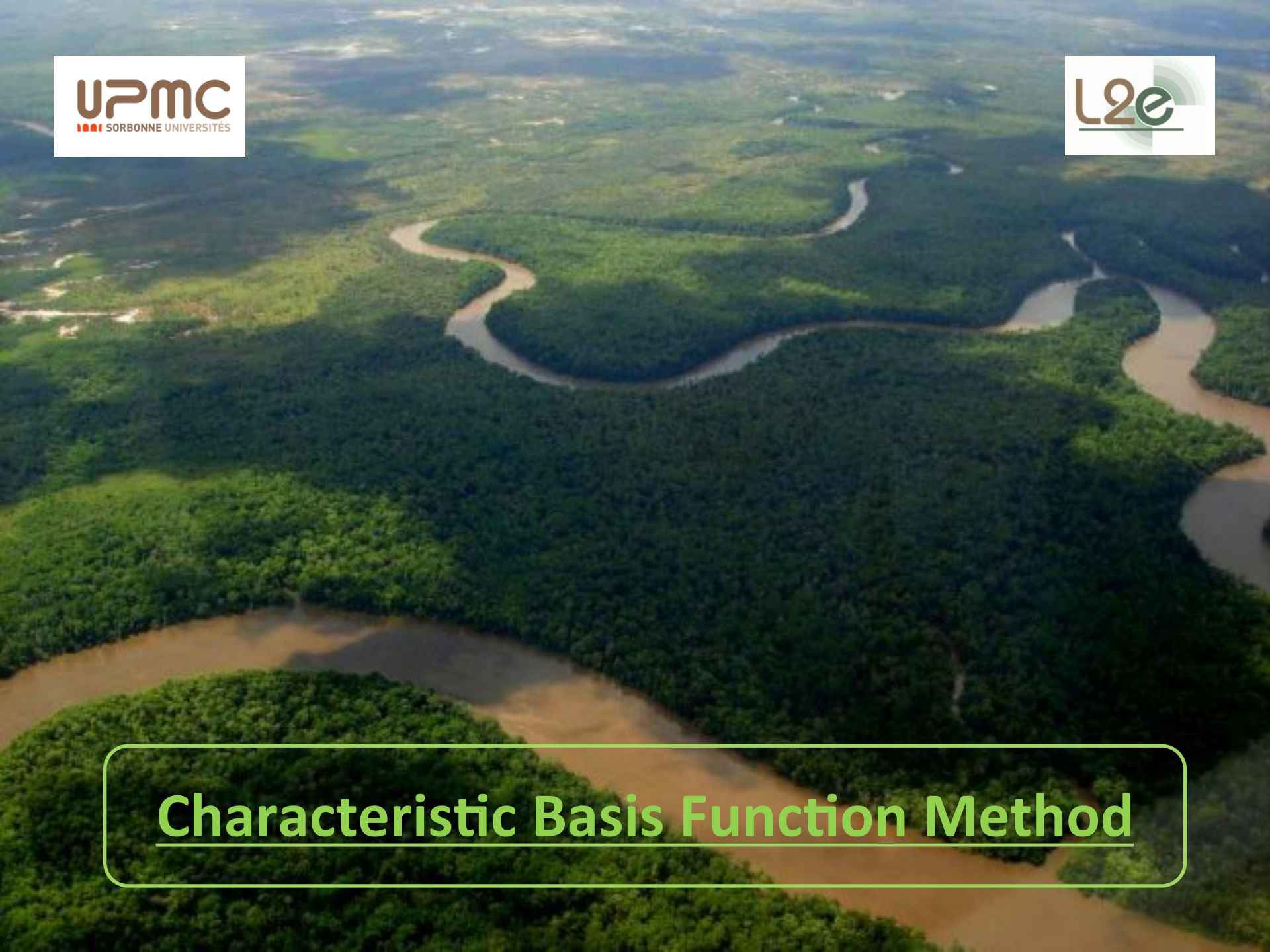
1.2. Numerical procedure

1.3. Factors affecting CBFM performances

2. The Multi-Level scheme of CBFM

3. Numerical Results

4. Conclusions and perspectives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Characteristic Basis Function Method

Plan

1. Characteristic Basis Function Method (CBFM)
   - 1.1. Motivations et advantages
   - 1.2. Numerical procedure
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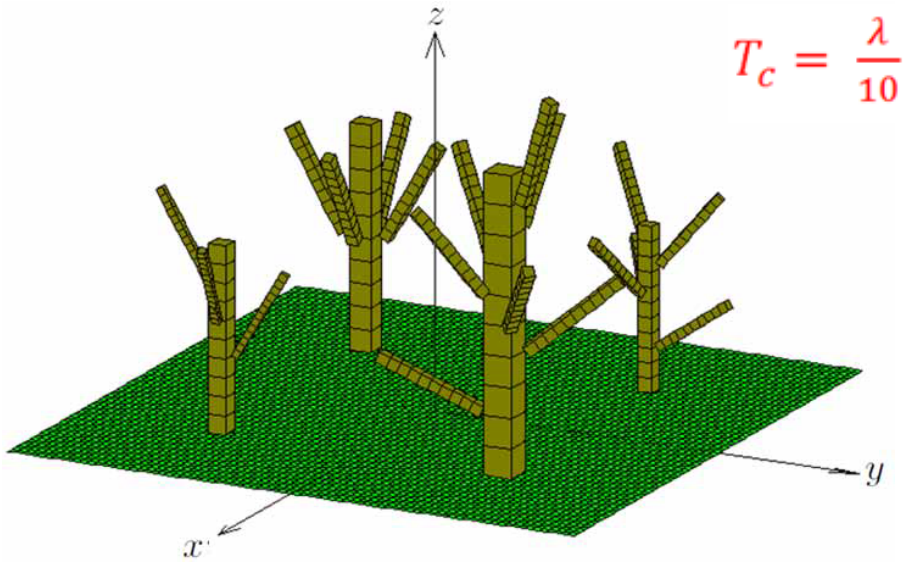
Motivations et advantages

3D full-wave model, based on the integral representation of the electric field (EFIE)



$$T_c = \frac{\lambda}{10} \quad , \quad \lambda = \frac{\lambda_0}{\sqrt{Re(\varepsilon_r)}}$$

* S. Bellez , Thèse de doctorat, UPMC 2010

Method of Moments (MoM)

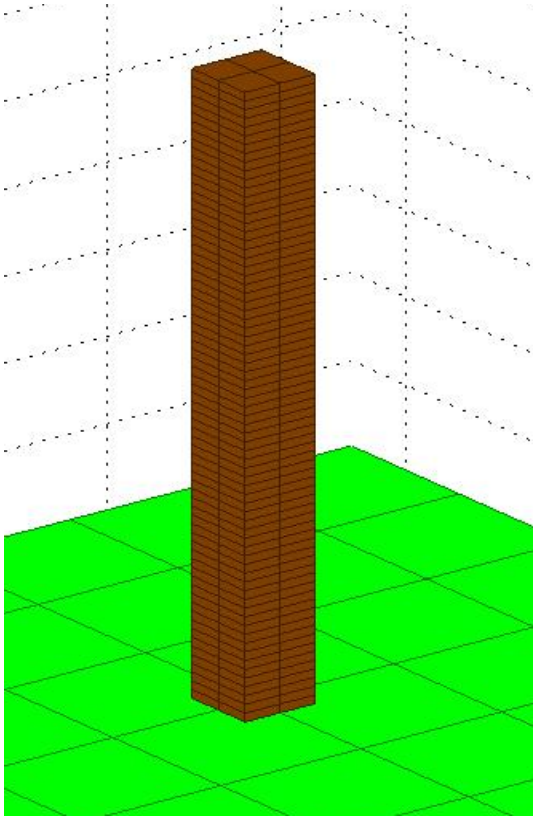
Integral representation of the total electric field :

$$\sum_{n=1}^{N} \sum_{q=1}^{3} Z_{pq}^{mn} E_q^n = E_p^{ref,m} \quad \text{p,q = x,y,z et m,n = [1,.....,Nb}_c\text{]} \quad \bar{r}'$$

$$\bar{\Omega}$$

Motivations et advantages

3D full-wave model, based on the integral representation of the electric field (EFIE)



Tree trunk discretized into **N** elementary cubic cells.

MoM

$$\begin{pmatrix} \begin{bmatrix} Z_{xx}^{11} & Z_{xy}^{11} & Z_{xz}^{11} \\ Z_{yx}^{11} & Z_{yy}^{11} & Z_{yz}^{11} \\ Z_{zx}^{11} & Z_{zy}^{11} & Z_{zz}^{11} \end{bmatrix} & \cdots & \begin{bmatrix} Z_{xx}^{1N} & Z_{xy}^{1N} & Z_{xz}^{1N} \\ Z_{yx}^{1N} & Z_{yy}^{1N} & Z_{yz}^{1N} \\ Z_{zx}^{1N} & Z_{zy}^{1N} & Z_{zz}^{1N} \end{bmatrix} \\ \vdots & \ddots & \vdots \\ \begin{bmatrix} Z_{xx}^{N1} & Z_{xy}^{N1} & Z_{xz}^{N1} \\ Z_{yx}^{N1} & Z_{yy}^{N1} & Z_{yz}^{N1} \\ Z_{zx}^{N1} & Z_{zy}^{N1} & Z_{zz}^{N1} \end{bmatrix} & \cdots & \begin{bmatrix} Z_{xx}^{NN} & Z_{xy}^{NN} & Z_{xz}^{NN} \\ Z_{yx}^{NN} & Z_{yy}^{NN} & Z_{yz}^{NN} \\ Z_{zx}^{NN} & Z_{zy}^{NN} & Z_{zz}^{NN} \end{bmatrix} \end{pmatrix}$$

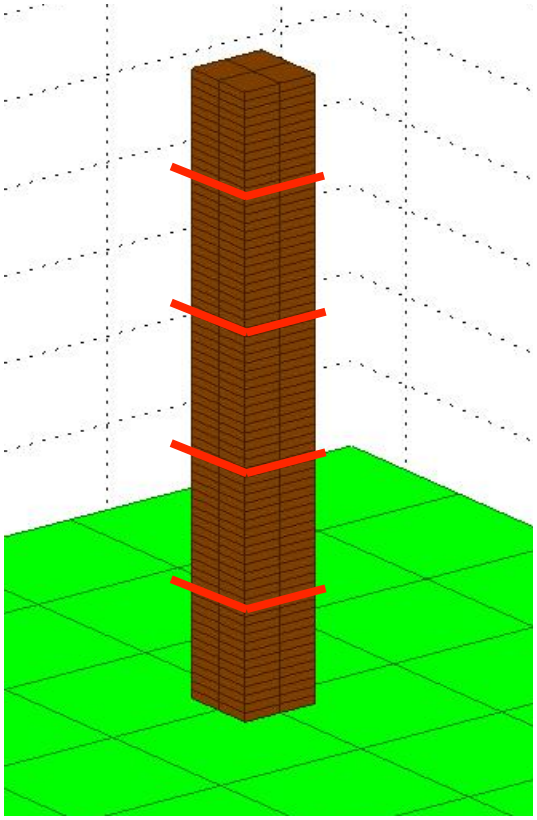
Z is the **3N**x**3N** matrix representing the **interactions** between the different cells in the object.

Linear system resolution

The use of this model is limited to few trees and to low frequencies **($N_{max} \approx 13\,000$)**

Motivations et advantages

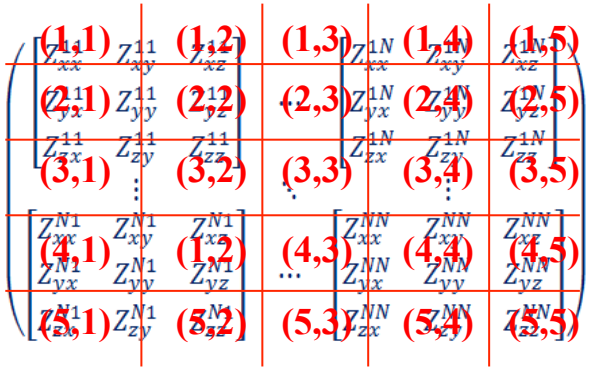
3D full-wave model, based on the integral representation of the electric field (EFIE)



Tree trunk discretized into **N** elementary cubic cells.

CBFM

Division of the 3D scatterer geometry into M patches



Via CBFM procedure

Reduced matrix

Improvement of the performances of the 3D model in terms of computation time and memory consumption

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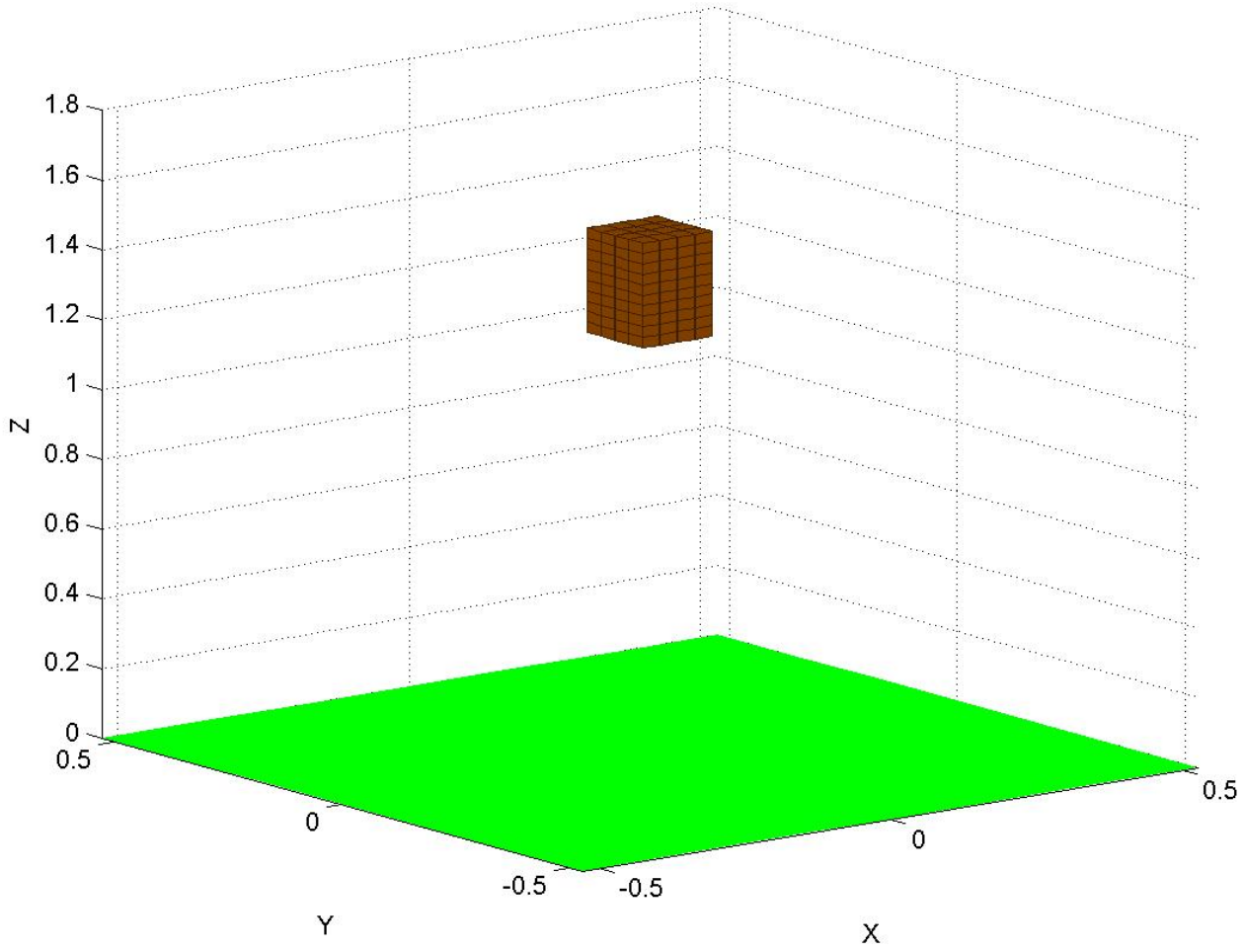
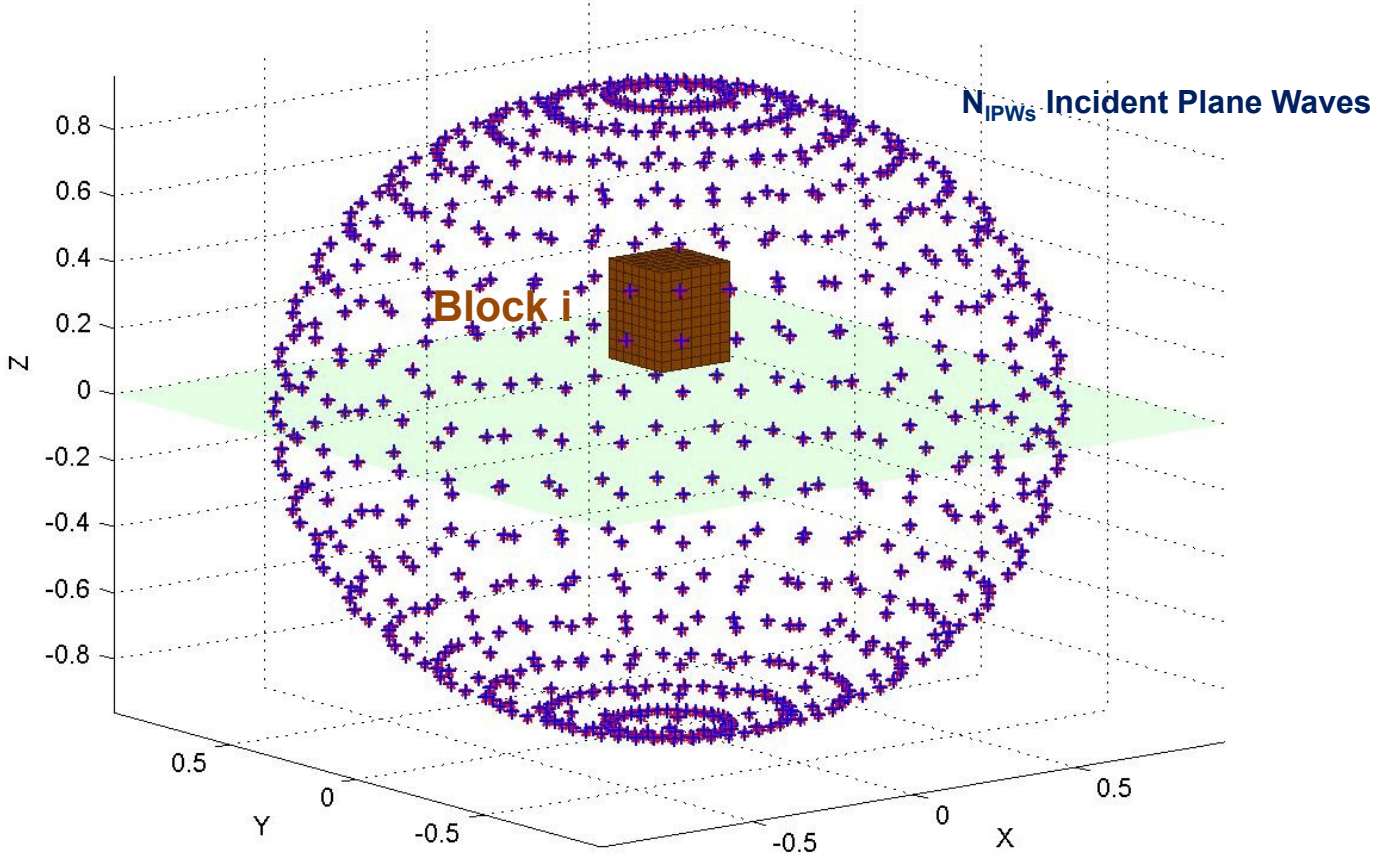
Numerical procedure



Numerical procedure

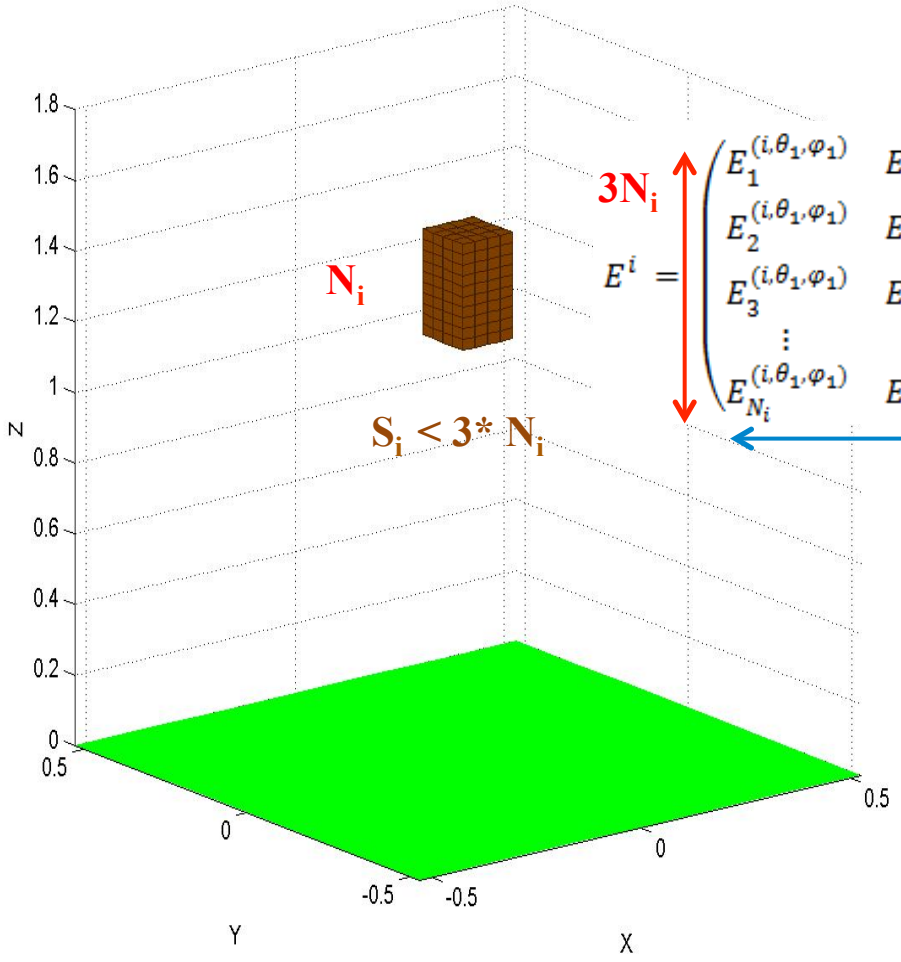
Generation of the Macro-Basis Functions (MBFs)



$$Z_{ii} \cdot E_{ii}^{MBFs} = E_{ii}^{ref,IPWs}$$

Numerical procedure

Generation of the Characteristic Basis Functions (CBFs)



N_i

$S_i < 3^* N_i$

$3N_i$

$$E^i = \begin{pmatrix} E_1^{(i,\theta_1,\varphi_1)} & E_1^{(i,\theta_2,\varphi_1)} & \cdots & E_1^{(i,\theta_{N\theta},\varphi_1)} & E_1^{(i,\theta_1,\varphi_2)} & \cdots & E_1^{(i,\theta_{N\theta},\varphi_{N\varphi})} \\ E_2^{(i,\theta_1,\varphi_1)} & E_2^{(i,\theta_2,\varphi_1)} & \cdots & E_2^{(i,\theta_{N\theta},\varphi_1)} & E_2^{(i,\theta_1,\varphi_2)} & \cdots & E_2^{(i,\theta_{N\theta},\varphi_{N\varphi})} \\ E_3^{(i,\theta_1,\varphi_1)} & E_3^{(i,\theta_2,\varphi_1)} & \cdots & E_3^{(i,\theta_{N\theta},\varphi_1)} & E_3^{(i,\theta_1,\varphi_2)} & \cdots & E_3^{(i,\theta_{N\theta},\varphi_{N\varphi})} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ E_{N_i}^{(i,\theta_1,\varphi_1)} & E_{N_i}^{(i,\theta_2,\varphi_1)} & \cdots & E_{N_i}^{(i,\theta_{N\theta},\varphi_1)} & E_{N_i}^{(i,\theta_1,\varphi_2)} & \cdots & E_{N_i}^{(i,\theta_{N\theta},\varphi_{N\varphi})} \end{pmatrix}$$

2^*N FWs

Singular Value Decomposition (SVD)

+

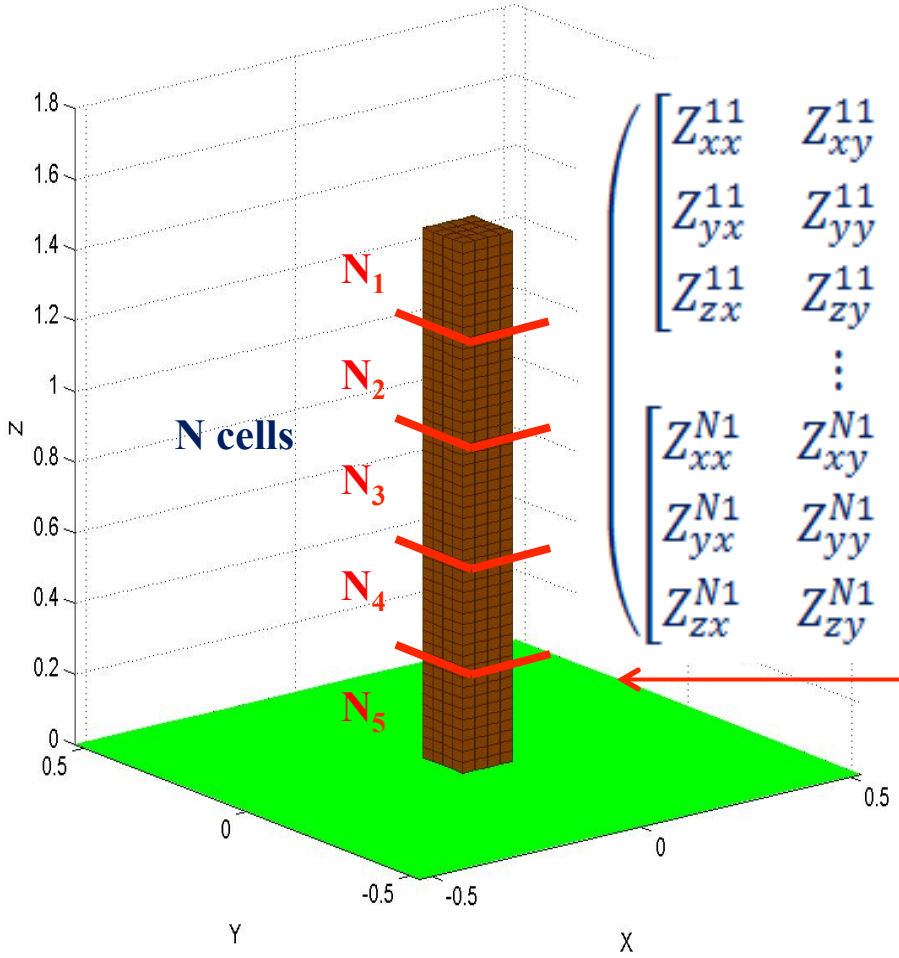
Normalization and thresholding (10^{-3})

=

S_i characteristic basis functions (CBFs) for the block i

Numerical procedure

Generation of the reduced matrix equation



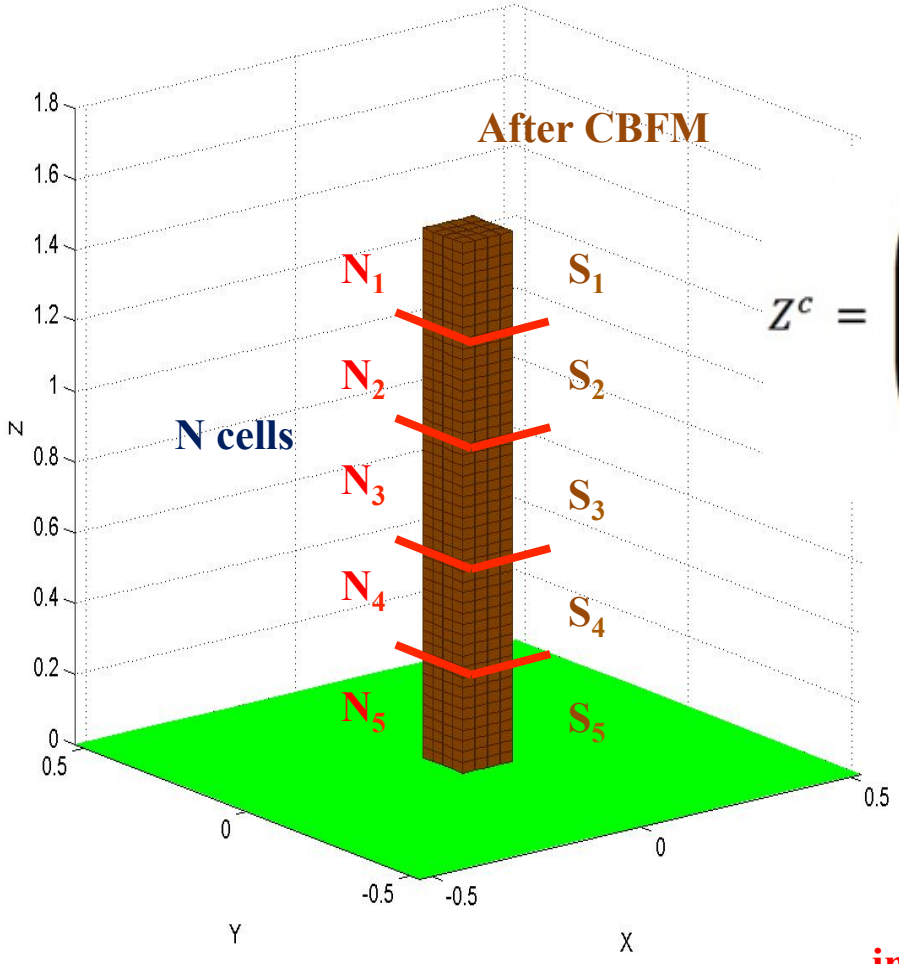
$$\begin{pmatrix} \begin{bmatrix} Z_{xx}^{11} & Z_{xy}^{11} & Z_{xz}^{11} \\ Z_{yx}^{11} & Z_{yy}^{11} & Z_{yz}^{11} \\ Z_{zx}^{11} & Z_{zy}^{11} & Z_{zz}^{11} \end{bmatrix} & \cdots & \begin{bmatrix} Z_{xx}^{1N} & Z_{xy}^{1N} & Z_{xz}^{1N} \\ Z_{yx}^{1N} & Z_{yy}^{1N} & Z_{yz}^{1N} \\ Z_{zx}^{1N} & Z_{zy}^{1N} & Z_{zz}^{1N} \end{bmatrix} \\ \vdots & \ddots & \vdots \\ \begin{bmatrix} Z_{xx}^{N1} & Z_{xy}^{N1} & Z_{xz}^{N1} \\ Z_{yx}^{N1} & Z_{yy}^{N1} & Z_{yz}^{N1} \\ Z_{zx}^{N1} & Z_{zy}^{N1} & Z_{zz}^{N1} \end{bmatrix} & \cdots & \begin{bmatrix} Z_{xx}^{NN} & Z_{xy}^{NN} & Z_{xz}^{NN} \\ Z_{yx}^{NN} & Z_{yy}^{NN} & Z_{yz}^{NN} \\ Z_{zx}^{NN} & Z_{zy}^{NN} & Z_{zz}^{NN} \end{bmatrix} \end{pmatrix}$$

3 N

3 N

Numerical procedure

Generation of the reduced matrix equation



$$Z^c = \begin{pmatrix} C^{(1)t} Z_{11} C^{(1)} & \dots & C^{(1)t} Z_{15} C^{(5)} \\ C^{(2)t} Z_{21} C^{(1)} & \dots & C^{(2)t} Z_{25} C^{(5)} \\ C^{(3)t} Z_{31} C^{(1)} & \dots & C^{(3)t} Z_{35} C^{(5)} \\ \vdots & \ddots & \vdots \\ C^{(5)t} Z_{51} C^{(1)} & \dots & C^{(5)t} Z_{55} C^{(5)} \end{pmatrix}$$

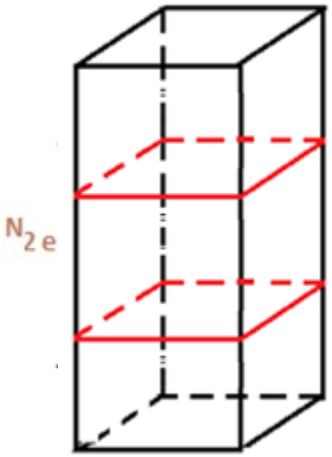
K

$K = S_1 + S_2 + S_3 + S_4 + S_5 \ll 3*N$

Solving the reduced matrix equation

Computation of the total electric field inside the scatterers and the scattered field

Numerical procedure

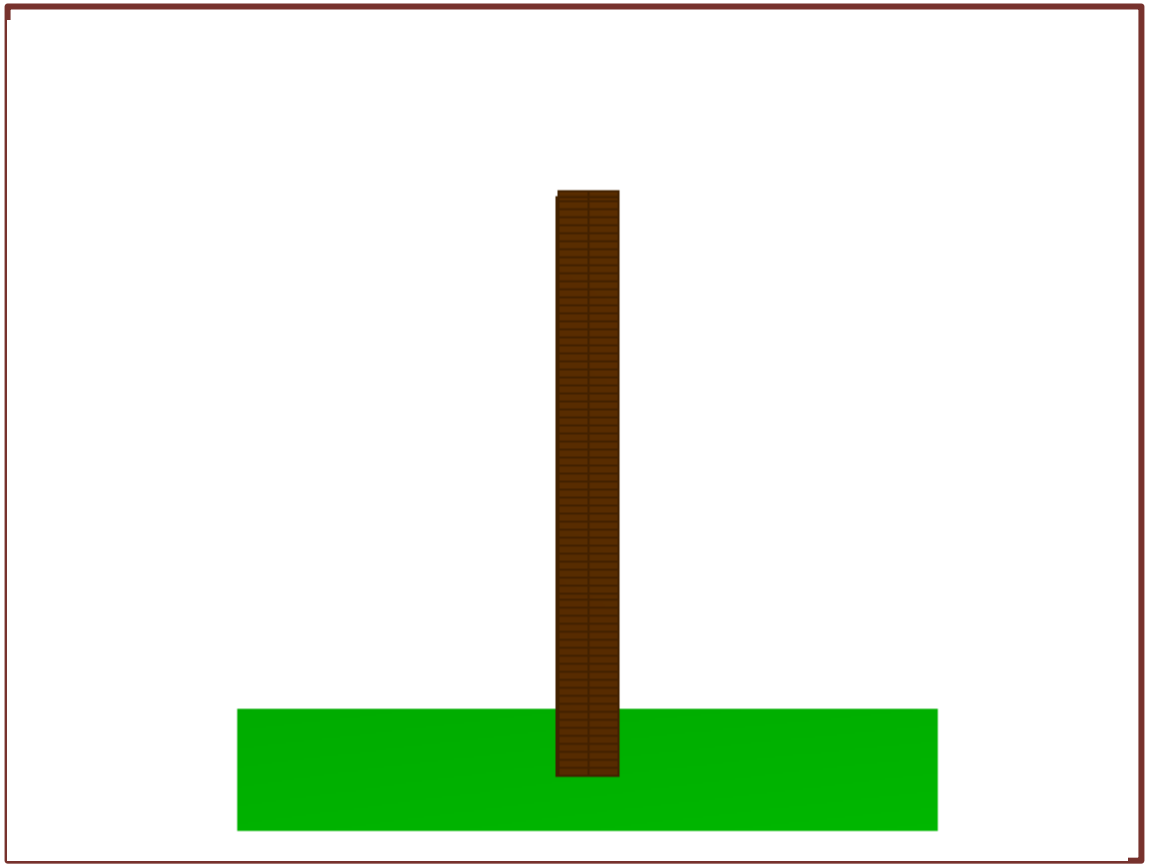


(1,1)	(1,2)	(1,3)
(2,1)	(2,2)	(2,3)
(3,1)	(3,2)	(3,3)

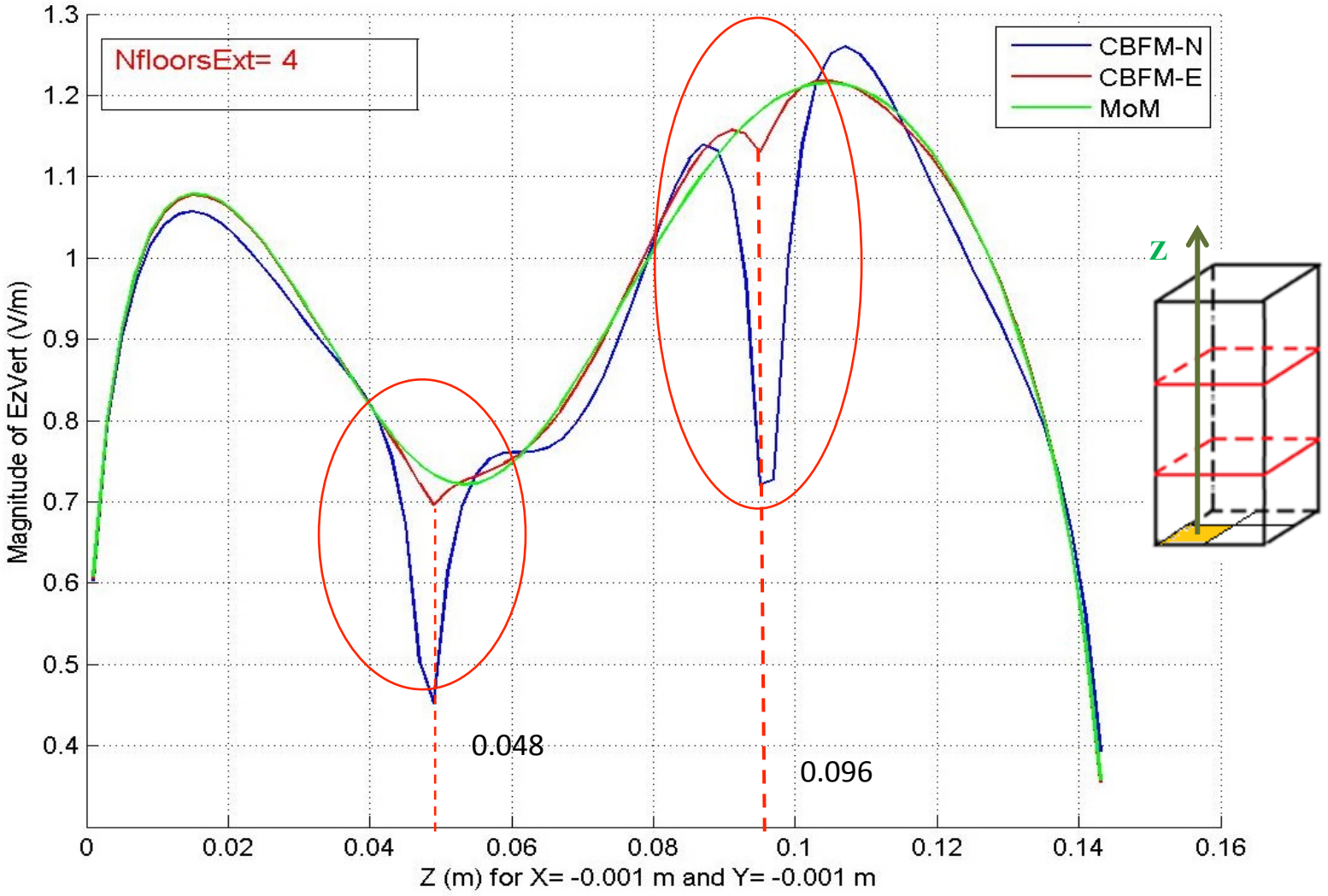
$N_{i,e}$ while generating the CBFs → N_i while generating Z^c

Validation on a simple example

Simple EM problem of 288 cells placed on a real ground (ε_g=5+j.3,6)



Validation on a simple example



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Factors affecting the CBFM performances

In order to evaluate the performances of the CBFM, we defined :

* Compression Rate :

$$CR = \frac{Size\ of\ Z_{MoM}}{Size\ of\ Z_{red}}$$

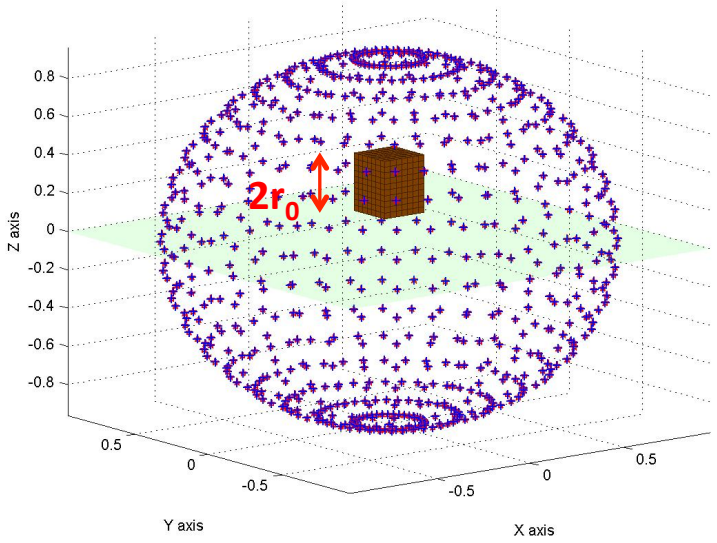
* Computation time : Time needed to compute the total electric field inside the scatterers

* Relative error comparing to **MoM** :

$$E_r = \frac{1}{N_p} \sum_{i=1}^{N_p} \frac{\left| E^i_{CBFM} - E^i_{MoM} \right|}{\left| E^{max}_{CBFM,MoM} \right|}$$

Factors affecting the CBFM performances

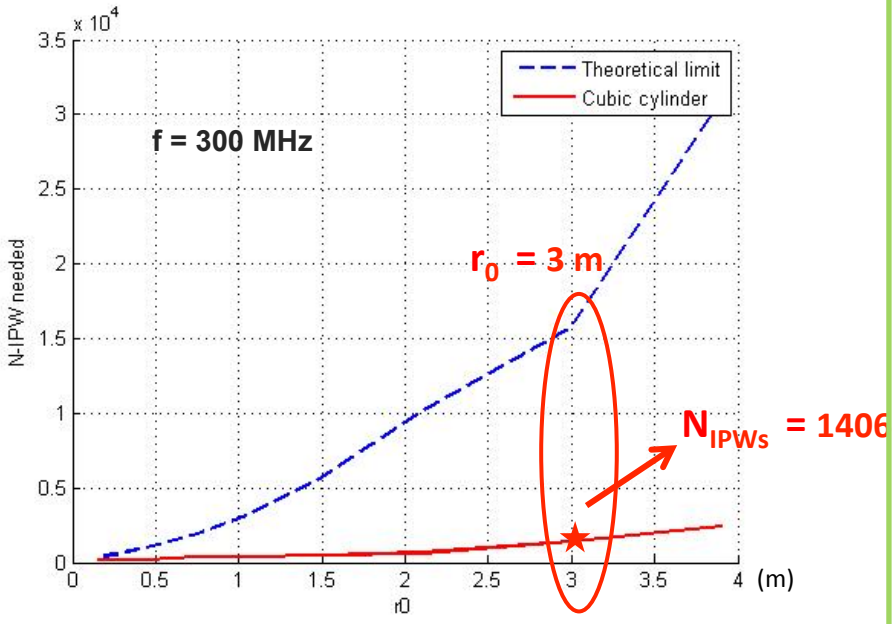
The number of plane waves N_{IPWs}



A block illuminated by N_{IPWs} **plane waves** in order to calculate the MBFs

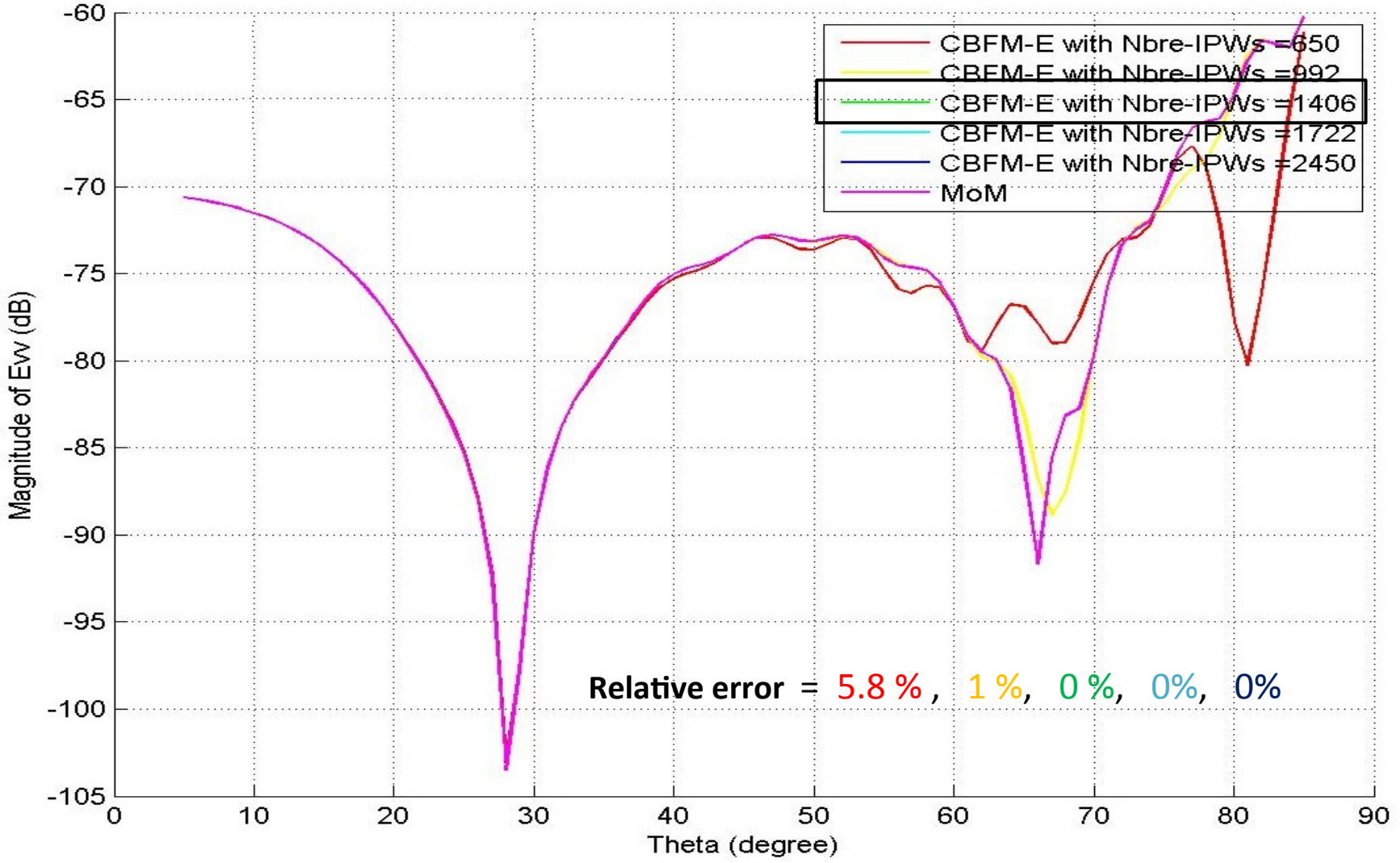
Theoretically, the maximum number of plane waves to saturate the SVD is in this order :

$$N_{IPWs} = 4 * (k\, r_0 + 2\pi)^2$$



Number of plane waves required for different block size

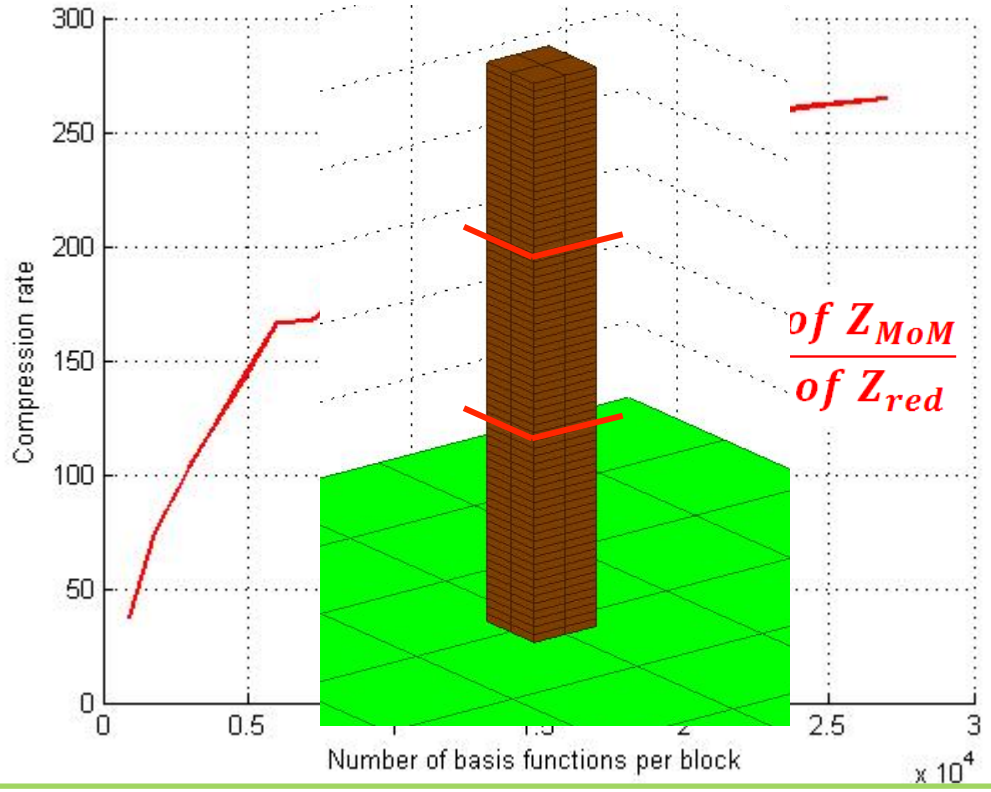
Factors affecting the CBFM performances



Factors affecting the CBFM performances

The number and size of the CBFM blocks

Computation time → Memory consumption

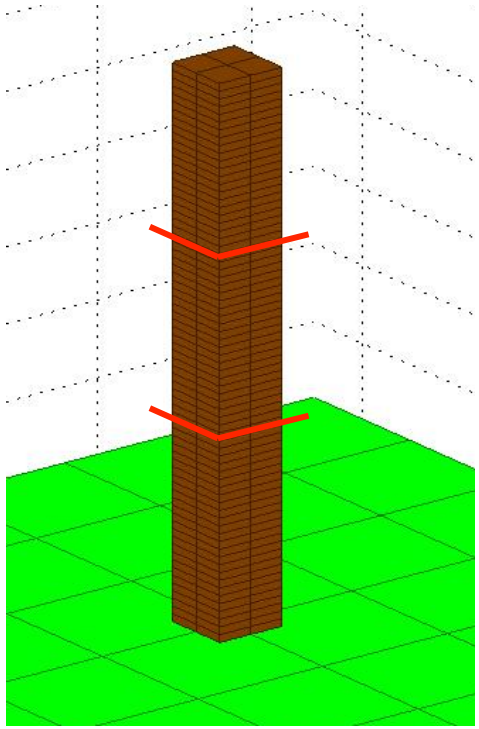


Factors affecting the CBFM performances

The number and size of the CBFM blocks

Computation time

Memory consumption



A prohibitive computational cost because of the great number of unknowns per block + the great number of IPWs needed

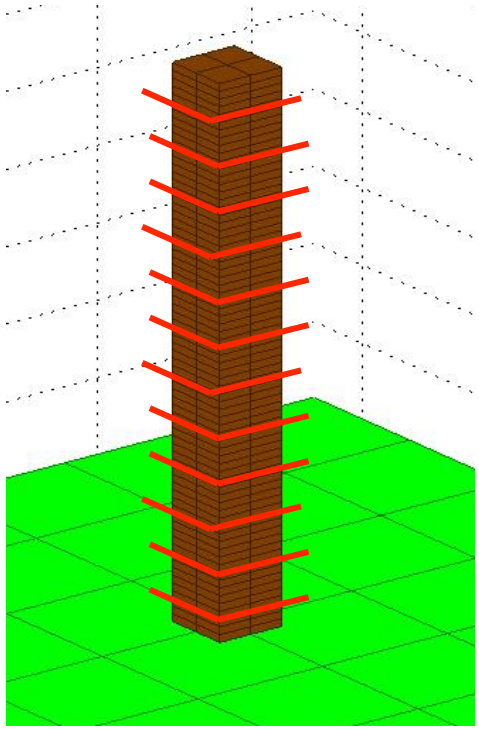
Small memory consumption thanks to an important compression rate

Factors affecting the CBFM performances

The number and size of the CBFM blocs

Computation time

Memory consumption



Number of plane waves ↘

Number of unknowns ↘

Parallelism ↗

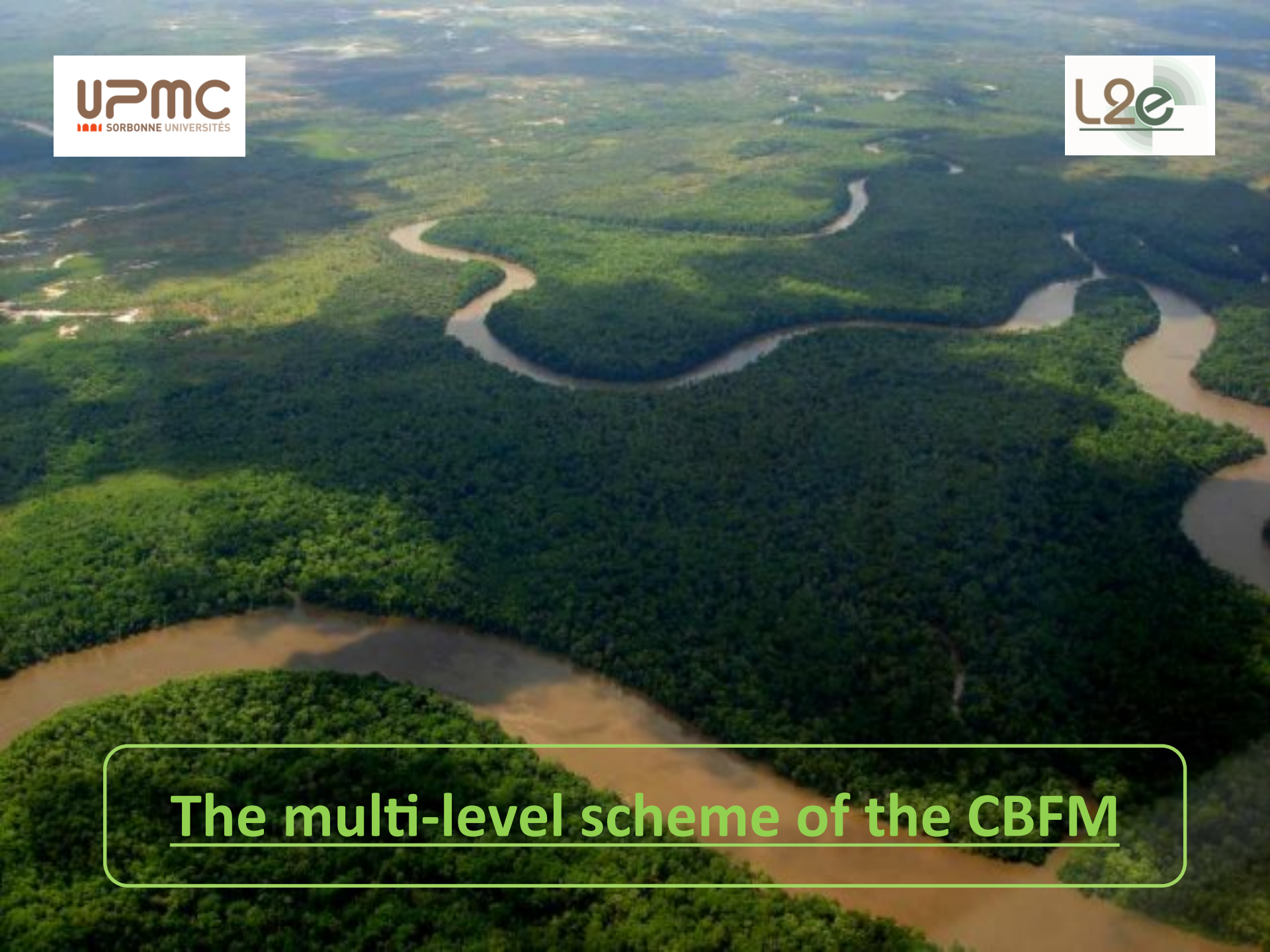
↓

Computational time ↘

Compression rate ↘

↓

Memory consumption ↗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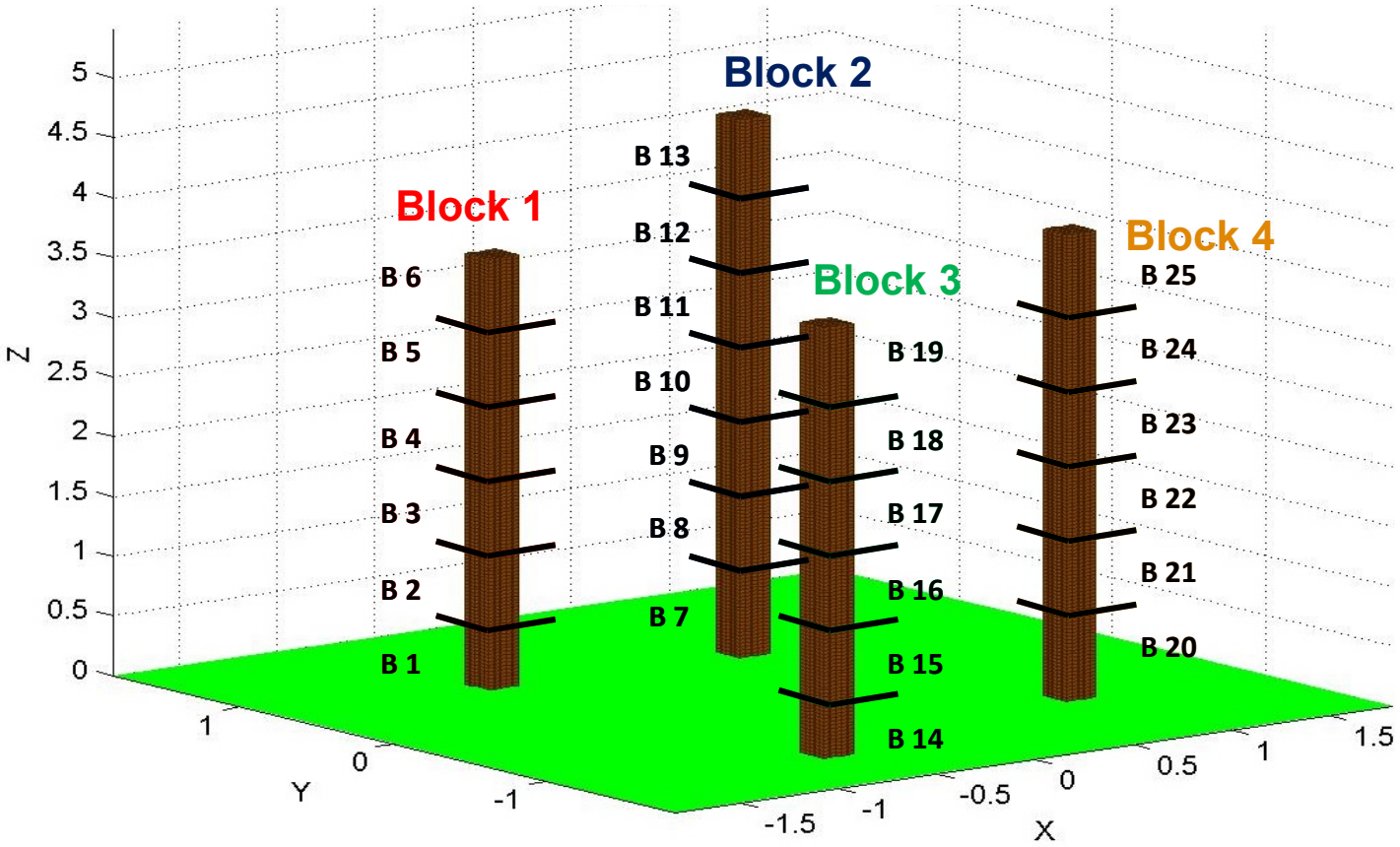
The multi-level scheme of the CBFM

Multi-level scheme of the CBFM

SOLUTION : The multi-level CBFM

Use of large blocks resulting on an important compression rate without great time consuming

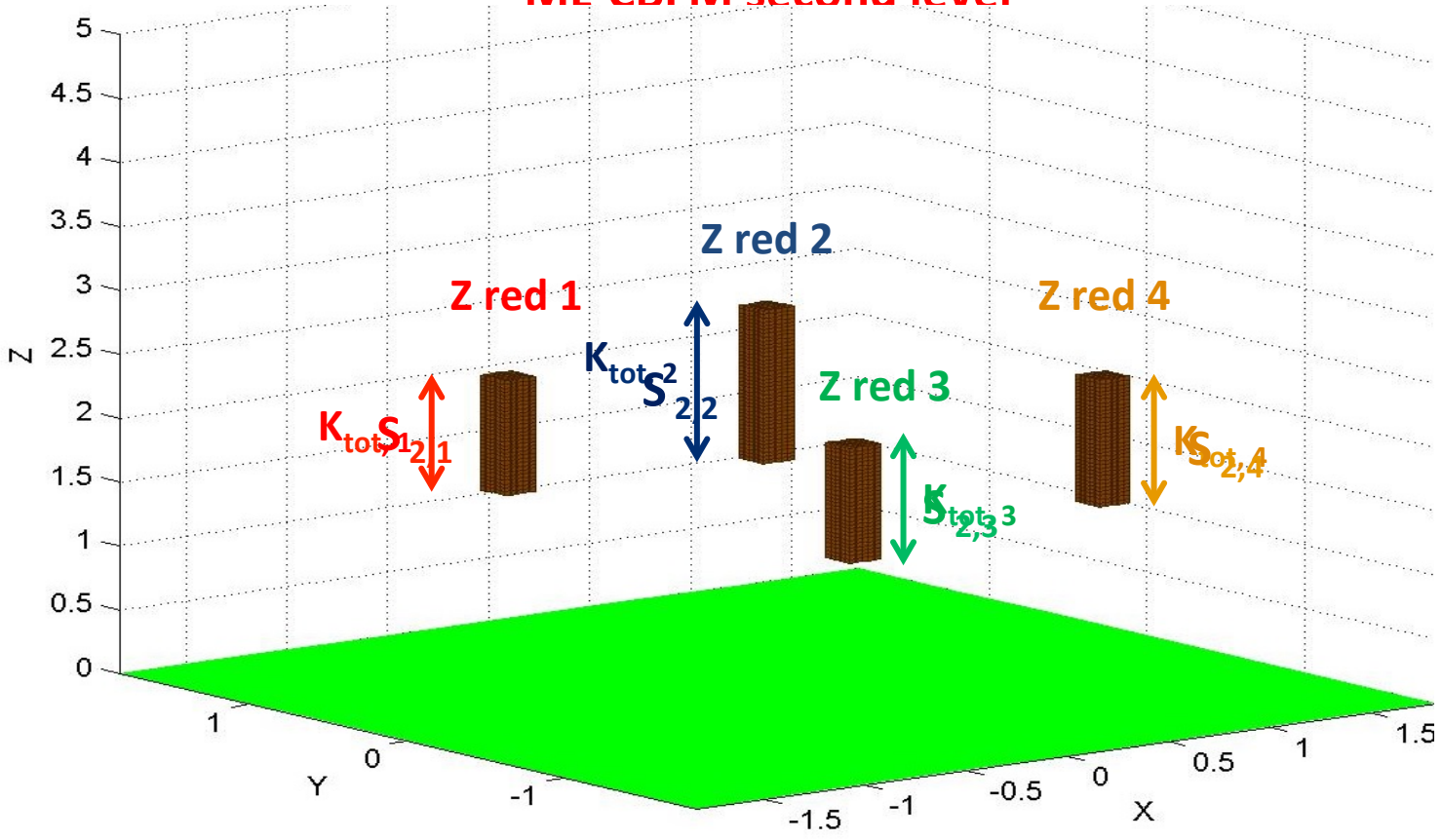
ME-CBFM first level :



Multi-level scheme of the CBFM

SOLUTION : The multi-level CBFM

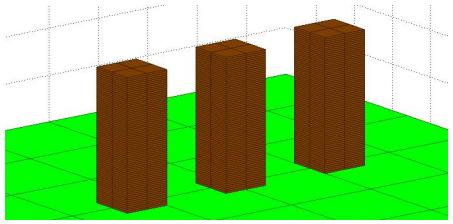
ML-CBFM second level



Final reduced matrix : $K_2 * K_2$ where $K_2 = \sum S_{2,i}$

Numerical results

Numerical Results

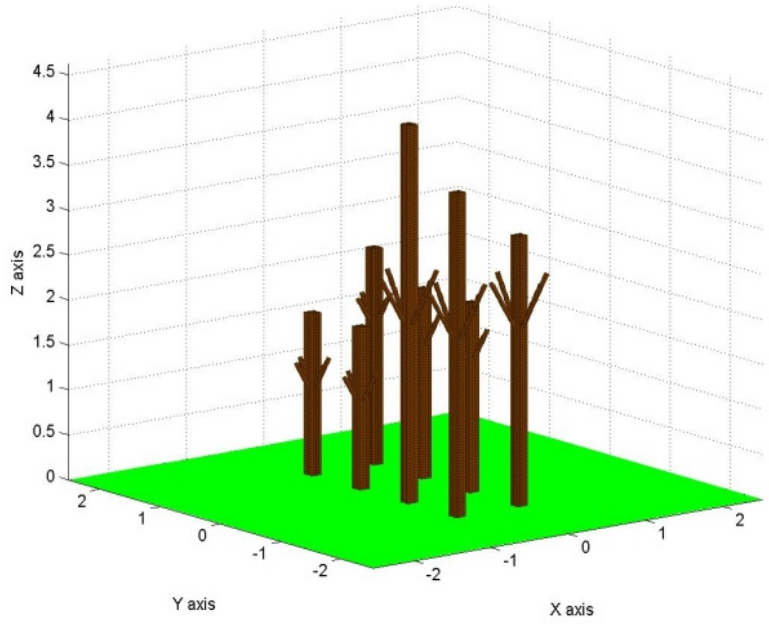


8 Dual Core AMD + Shared memory architecture
39 GB of RAM + 49 GB of SWAP
Intel **Fortran** Composer 2013 - 64 bits (**OpenMP**)

Block 1	Block 2	Block 3	Block 4	... ...	Block N_b
N_1 Inversion + SVD + Threshold	N_2 Inversion + SVD + Threshold	N_3 Inversion + SVD + Threshold	N_4 Inversion + SVD + Threshold		N_{N_b} Inversion + SVD + Threshold

Reduced matrix

Numerical Results

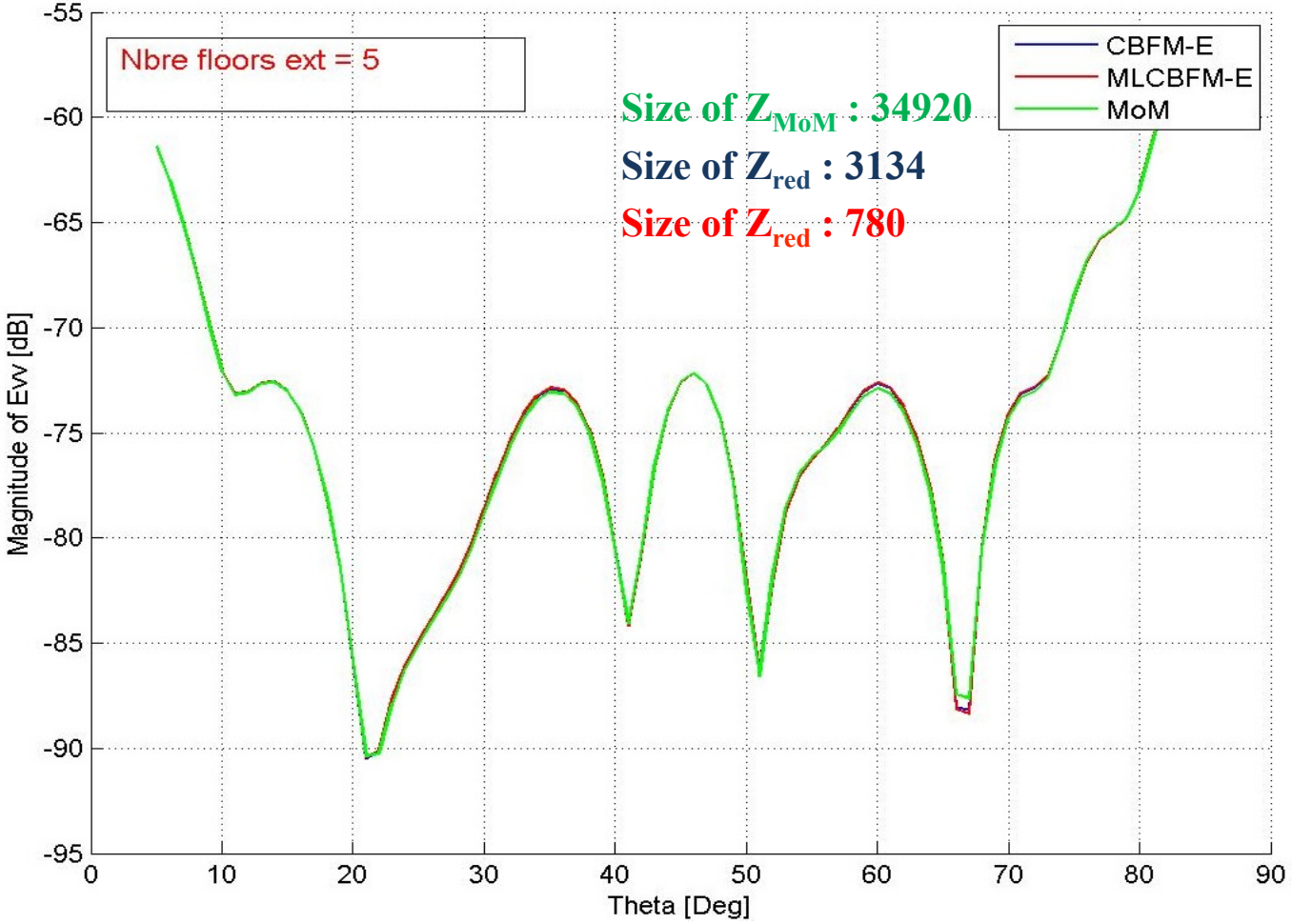


Simulation1 : 40 cylinders modeling 8 trees

Frequency	300 MHz
Number of cylinders	40
Scatterers Permittivity	9.6 + i * 0.01
Ground permittivity	5 + i * 2.1
λ scatterer	0.323 m
Size of cells	0.03 m
N cells	11640 cells
N blocks	114
N_z floors per block	10
N_z extended floors	5
N_{IPW}	380
Threshold σ	10^{-3}
Number of levels and of blocks per level :	**3 : [114,40,8]**

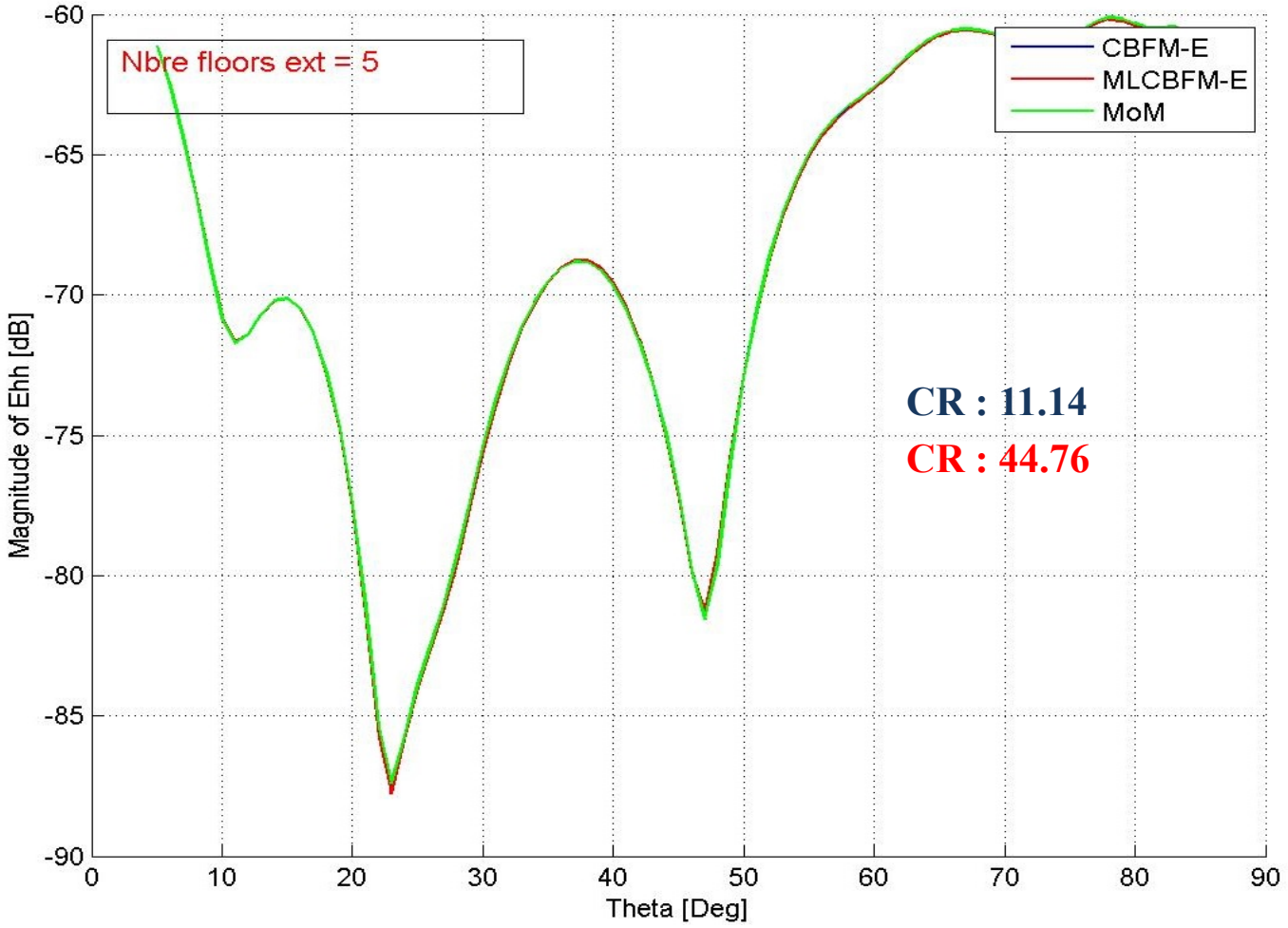
Numerical Results

EM problem of 11640 cells computed with 3 levels of CBFM-E

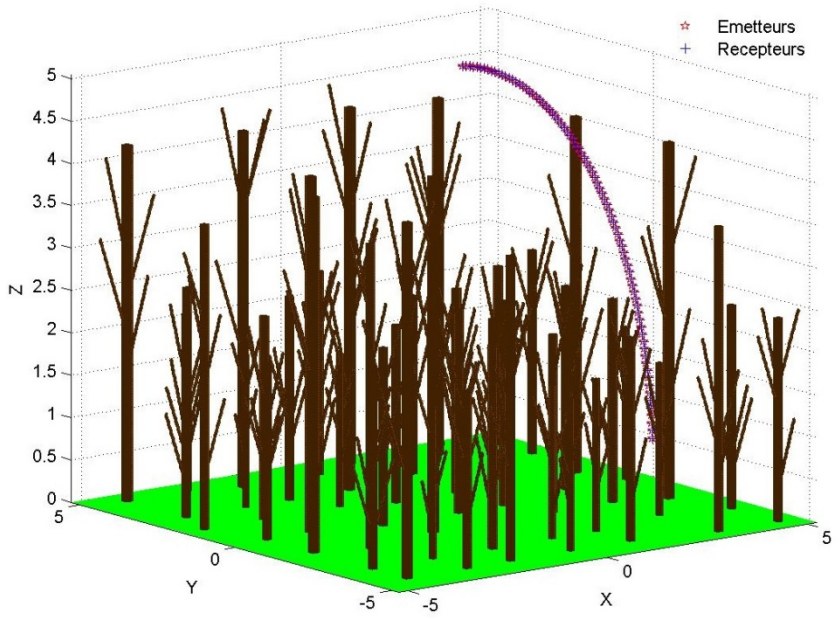


Numerical Results

EM problem of 11640 cells computed with 3 levels of CBFM-E



Numerical Results

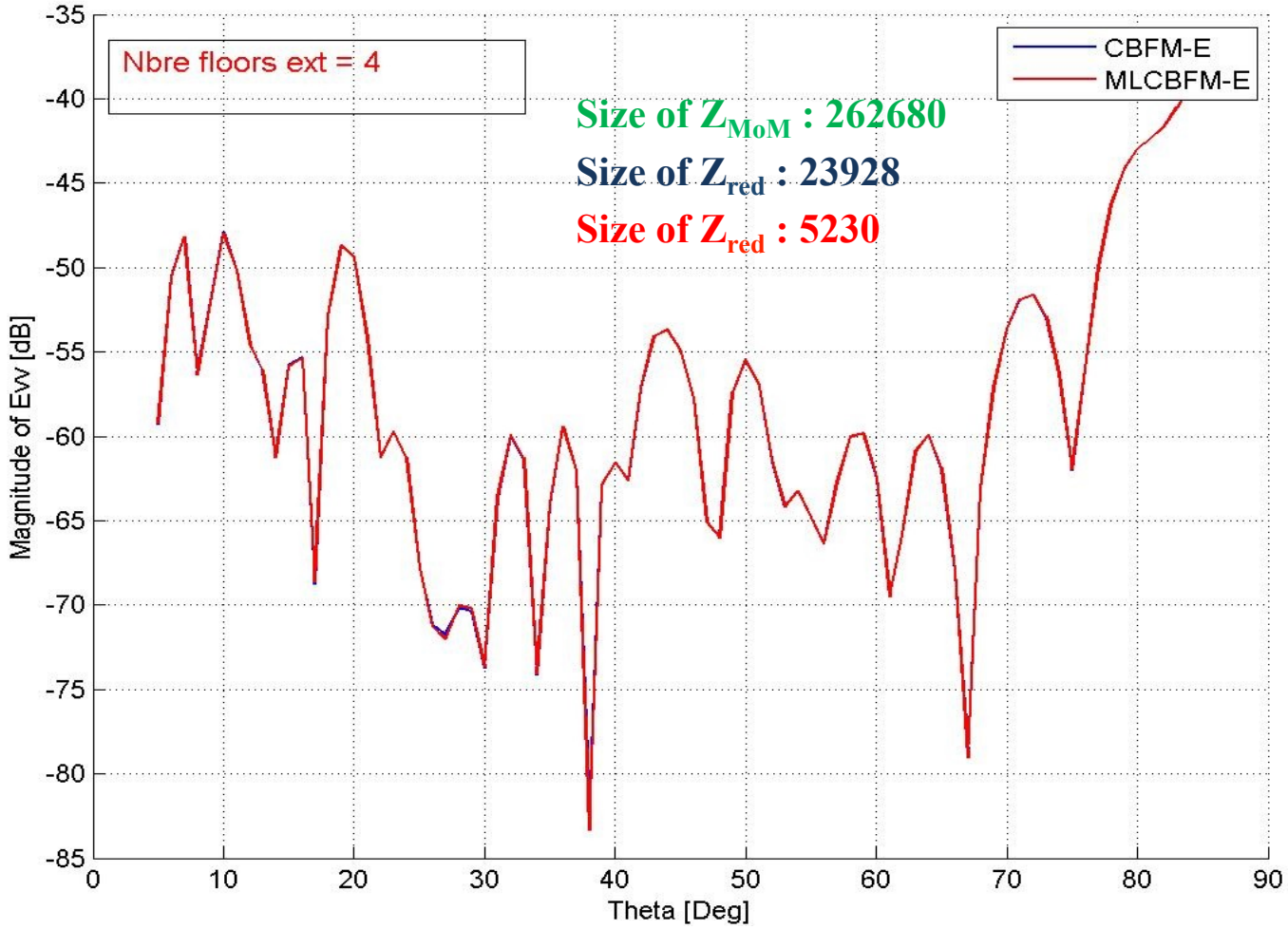


Simulation 2 : 245 cylinders modeling 49 trees with 4 branches each

Frequency	300 MHz
Number of cylinders	245
Scatterers Permittivity	9.6 + i * 0.01
Ground permittivity	5 + i * 2.1
λ scatterer	0.323 m
Size of cells	0.03 m
N cells	87560 cellules
N blocks	1043
N_z floors per block	10
N_z extended floors	4
N_{IPW}	380
Threshold σ	10^{-3}
Number of levels and of blocks per level :	**[1043, 245, 49]**

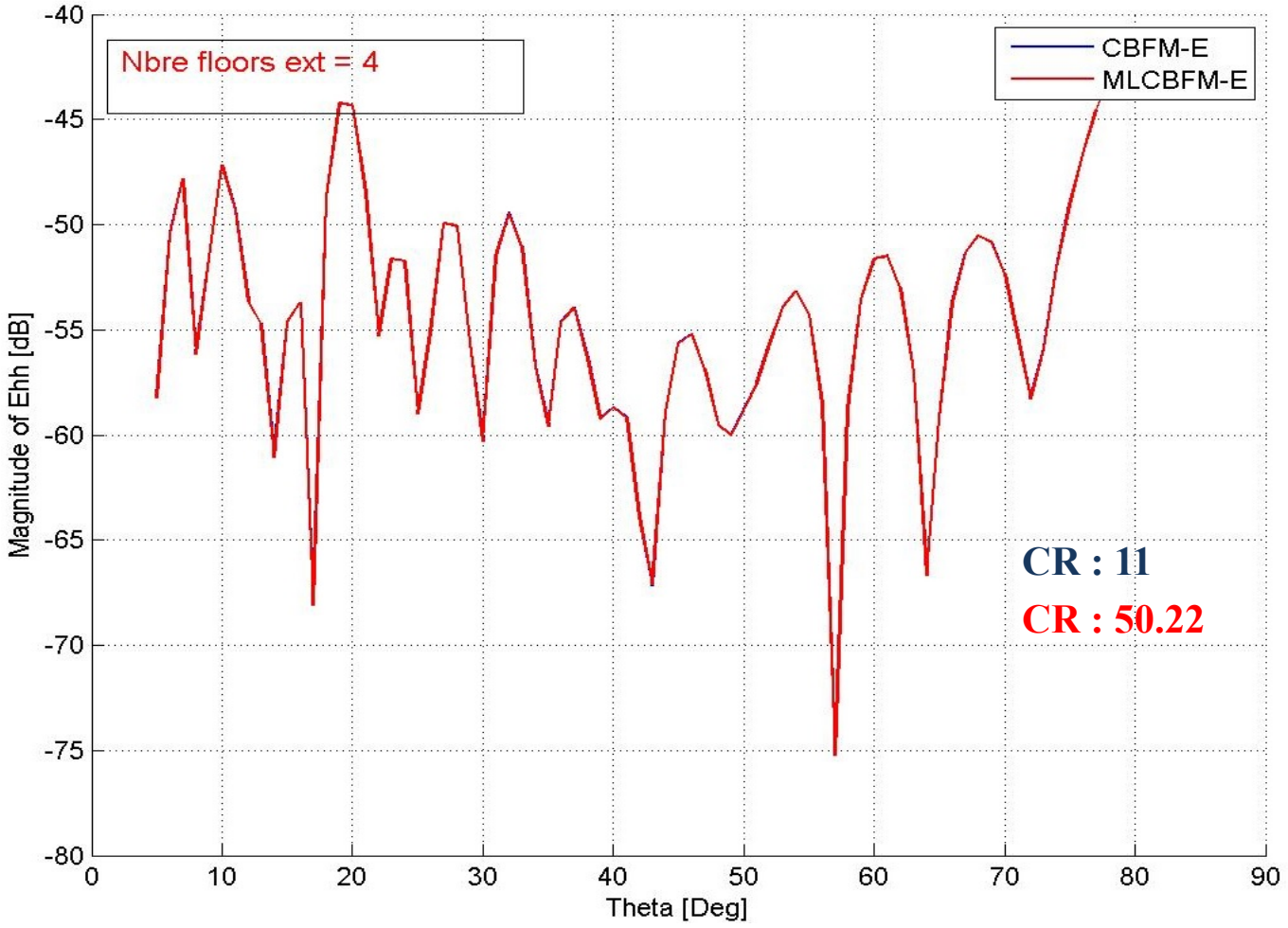
Numerical Results

EM problem of 87560 cells computed with 3 levels of CBFM-E



Numerical Results

EM problem of 87560 cells computed with 3 levels of CBFM-E



Numerical Results

		CBFM-E	MLCBFM-E	MoM
Simulation 1 (11640 cells)	Computing Time	2 min 15 s	1 min 48 s	2 h 28 min
	Size of Z_{red}	3134	780	--
	Compression Rate	11.14	44.76	1
Simulation 2 (87560 cells)	Computing time	1 h 12 min	28 m 28 S	
	Size of Z_{red}	23928	5230	
	Compression Rate	11	50.22	

Conclusion and perspectives

Conclusions and perspectives

Parallelized Multilevel Characteristic Basis Function Method Applied to Scattering Model for Forest Remote Sensing

CBFM-E **MLCBFM-E**

✓ Preservation of the **accuracy** of the results comparing to **MoM** .

✓ Significant **reduction** of the **computation time** thanks to the **parallelization** of the CBFM

✓ Significant **reduction** of **memory resources needed** thanks to an important **compression rate** achieved in particular by the **ML-CBFM-E**

Parallelization **MPI** of the MLCBFM-E

Eventual hybridation with the **ACA**

Comparison to measurements and eventual application of the model on data inversion and target detection

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Thanks for your attention

Parallelized Multilevel Characteristic Basis Function Method Applied to Scattering Model For Forest Remote Sensing

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